Theoretical Observation of Two State Lasing from InAs/InP Quantum-Dash Lasers

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***Abstract*-The effect of cavity length on the lasing wavelength of InAs/InP quantum dash (Qdash) laser is examined using the carrier-photon rate equation model including the carrier relaxation process from the Qdash ground state and excited state. Both, homogeneous and inhomogeneous broadening has been incorporated in the model. We show that ground state lasing occurs with longer cavity lasers and excited state lasing occurs from relatively short cavity lasers.**

I. Introduction

Long wavelength emission from InAs-InP quantum dot (Qdot) and Qdash lasers has attracted its potential application in the optical communications. Thanks to the impressive progress in the fabrication of Qdot/Qdash based lasers that have resulted in lasers with low threshold current density, high differential gain, etc. [1]. Moreover, the recently reported broadband emission from Qdash lasers spanning ~75nm bandwidth at relatively high emission power in C- and L-bands further strengthened their possible application in replacing multiple DFB lasers with a single wavelength-filtered Qdash laser for long haul optical communications [2]. Many experimental studies have been carried out on Qdash lasers since the last decade; however, little work on the theoretical modeling of these devices has been reported [3-5]. This might possibility due to the quasi zero dimensional density of states (DOS) of Qdashes which has a high energy tail, and increased number of dash parameter requirement [6]. Very recently, we reported a rate equation model for Qdash lasers considering only a ground state (GS) energy level in the dashes [7]. Based on the model, we made an effort to explain the experimentally observed red shift of lasing wavelength with increasing cavity length by relating it to the inhomogeneous broadening.

In the work, we extend our model to include an excited state (ES) energy level of a dash, and then examine the spectral characteristics of the laser as a function of cavity length. Our results show two-state lasing at room temperature from the Qdash laser, which has not been observed experimentally except at low temperature [8].

II. Theory

The theoretical model developed is an extension to our previous work [7] by including ES of a Qdash. The model is based on the rate equations of each dash ensemble utilizing the procedure reported in [7, 9]. The dashes are grouped according to their resonant wavelength and a series of longitudinal cavity photon modes are considered. We consider a four level energy system consisting of the separate confinement heterostructure (SCH), the wetting layer (WL), the ES, and the GS of dashes with carrier populations N_S, N_W, $N_{j,k}^{ES}$, and $N_{j,k}^{GS}$, respectively. Both, the homogeneous Lorentzian broadening $B\left(E_m - E_{j,k}^{ES,GS}\right)$ with $\hbar\Gamma_{hom}$ full width at half maximum (FWHM) and inhomogeneous Gaussian broadening $G_{j,k}^{ES,GS}$ with Γ_{inh} FWHM [6,7], of the optical gain, is considered in the formulation. The model is as follows:

$$\frac{dN_S}{dt} = \frac{\eta_i I}{e} - \frac{N_S}{\tau_{SW}} - \frac{N_S}{\tau_S} + \frac{N_W}{\tau_{WS}} \quad (1)$$

$$\frac{dN_W}{dt} = \frac{N_S}{\tau_{SW}} + \sum_{j,k} \frac{N_{j,k}^{ES}}{\tau_{EW}^{j,k}} - \frac{N_W}{\overline{\tau_{WE}}} - \frac{N_W}{\tau_{WS}} - \frac{N_W}{\tau_W} \quad (2)$$

$$\frac{dN_{j,k}^{ES}}{dt} = \frac{N_W G_{j,k}^{ES}}{\tau_{WE}^{j,k}} + \frac{N_{j,k}^{GS}}{\tau_{GE}^{j,k}} - \frac{N_{j,k}^{ES}}{\tau_{EW}^{j,k}} - \frac{N_{j,k}^{ES}}{\tau_E} - \frac{N_{j,k}^{ES}}{\tau_{EG}^{j,k}} - \frac{c\Gamma}{n_a} \sum_m {}^{ES}g_m^{j,k} S_m \quad (3)$$

$$\frac{dN_{j,k}^{GS}}{dt} = \frac{N_{j,k}^{ES}}{\tau_{EG}^{j,k}} - \frac{N_{j,k}^{GS}}{\tau_{GE}^{j,k}} - \frac{N_{j,k}^{GS}}{\tau_G} - \frac{c\Gamma}{n_a} \sum_m {}^{GS}g_m^{j,k} S_m \quad (4)$$

$$\frac{dS_m}{dt} = \beta \sum_{k,j} B\left(E_m - E_{j,k}^{ES,GS}\right) \frac{N_{j,k}^{ES,GS}}{\tau_{Sp}} + \frac{c\Gamma}{n_a} \sum_{k,j} \left({}^{ES}g_m^{j,k} + {}^{GS}g_m^{j,k}\right) S_m - \frac{S_m}{\tau_p} \quad (5)$$

Eqs. (1) and (2) refer to the carrier dynamics in the SCH and the WL, whereas Eqs. (3) and (4) corresponds to the carrier dynamics in each of the intra-dash energy levels of ES and GS of the dash groups. The subscripts *j* and *k* refers to the j^{th} group of Qdash ensemble and its k^{th} intradash energy level. Eqn. (5) corresponds to the carrier photon density of the m^{th} mode including the spontaneous emission term and the photon loss. ${}^{ES,GS}g_m^{j,k}$ refers to the linear optical gain of the k^{th} state j^{th} dash group contributing to the m^{th} mode photons. More details of this parameters is available elsewhere [6, 7]. In brief, the linear gain incorporates the unique DOS N_D of dashes along with the homogeneous and the inhomogeneous, broadening terms. It is worth mentioning here that N_D and $G_{j,k}^{ES,GS}$ includes the unique features of the Qdash by considering the quantum wire (Qwire) like DOS function [6]. The carrier relaxation ($\tau_{SW}, \tau_{WE}, \tau_{EG}$), recombination lifetimes

TABLE I
QDASH LASER PARAMETERS USED IN SIMULATION

Parameter	Description	Value	Unit
L	Cavity length	1000	μm
d	Stripe width	50	μm
w_{WL}	Wetting layer thickness	1	nm
w_{DH}	Qdash width	18	nm
h_{DH}	Qdash height	3.2	nm
N_{lyr}	Number of Qdash layers	4	-
A_{eff}	Qdash effective crossection area	1.92e-12	cm^2
Γ	Confinement factor	0.02	-
$R_1=R_2$	Cleaved facet reflectivity	0.3	-
α_i	Internal modal loss	7.4	cm^{-1}
β	Spontaneous emission factor	1e-4	-
N_D	Qdash density of states	5e17	cm^{-3}
D_g	Qdash ground state degeneracy	1	-
D_e	Qdash excited state degeneracy	2	-
D_W	WL density of states	1.8e19	cm^{-3}
E_{ES}	ES transition energy	785	meV
E_{GS}	GS transition energy	755	meV
E_{WL}	WL ground state energy	860	meV
$\hbar\Gamma_{hom}$	Homogeneous broadening	5	meV
Γ_{inh}	Inhomogeneous broadening	25	meV
τ_{SW}	Relaxation time from SCH to WL	500	ps
τ_{WS}	Re-excitation time from WL to SCH	1	ns
τ_{WE0}	Initial capture time from WL to Qdash ES	1	ps
τ_{EG0}	Initial capture time from Qdash ES to GS	2	ps
τ_W	Recombination lifetime of WL	0.8	ns
τ_e, τ_g	Recombination lifetime of QDash	0.5	ns
τ_{Sp}	Spontaneous lifetime	2.8	ns
n_a	Refractive index	3.5	-

(τ_W, τ_E, τ_G), and other parameters utilized in the model are detailed in Table I. The photon lifetime τ_p is calculated according to [7] and the carrier re-excitation lifetimes are calculated utilizing the condition of detailed balance [9].

III. NUMERICAL RESULTS

The Qdash laser considered in this work is obtained from [2] and is based on the InAs/InP material system. The various dash and laser structure parameters used in the simulation are shown in Table I, most of which are taken from [6,7,9]. The steady state lasing spectra are obtained by solving the rate equations simultaneously using the fourth-order Runge-Kutta numerical method up to 9 ns. For simplicity, the recombination within the SCH is neglected ($\tau_S = \infty$). The separation between the dash groups is 0.295 meV and the number of dash group is 201 with 5 intra-dash energy levels.

Fig. 1(a) illustrates the effect of cavity length (L) on the central lasing wavelength (λ_C) calculated by identifying the central wavelength at the FWHM, while Fig. 1(b) shows the variation in the threshold current density (J_{th}) of the laser as a function of the cavity length. A clear two-state lasing at ~1.64 μm is observed in Fig. 1(a) for the longer cavity lengths (0.8 and 1.0 mm). Whereas lasing from the excited state ~1.59 μm is observed from relatively shorter cavity lasers of < 0.8 mm. For shorter devices the gain of GS transition is not enough to overcome the total loss (~34 cm^{-1} for L = 0.45 mm) and hence the lasing proceeds from the ES transition [10]. In other words, the DOS of GS is less than the DOS of ES (which is double degenerate) which in turn decreases the gain of GS by incorporating few carriers than required to overcome the total internal loss and hence ES lasing is observed from shorter cavities. However, for the case of longer cavities, the lower gain of GS probably compensates the total loss and lasing proceeds from the GS transition itself. If both GS and ES gain becomes comparable in longer cavities, simultaneous two state lasing might also be observed.

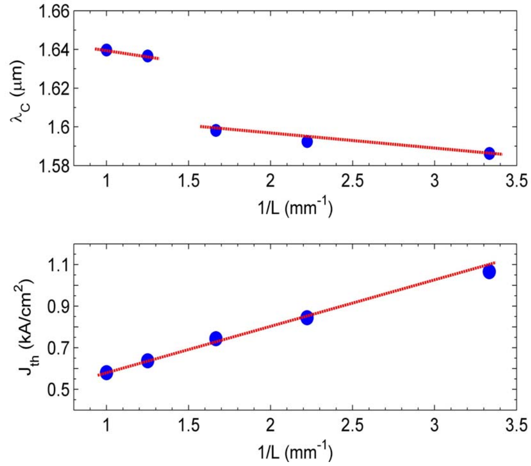

Fig. 1. Calculated (a) central lasing wavelength and (b) threshold current density of InAs/InP Qdash laser [2] at different cavity lengths. The lines are guide to eyes.

IV. CONCLUSION

In conclusion, we have implemented rate equation model to analyze the stimulated emission state of InAs/InP Qdash lasers. We theoretically show two-state lasing from the Qdash lasers with cavity length > 0.8 mm at room temperature.

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